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A NOTE ON MULTICYCLIC CONTROL
BY SWASHPLATE OSCILLATION

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Summary

This note describes the fundamental principles of multicyclic (higher harmonic) control by swashplate oscillation, and discusses advantages and constraints of this technique. A simplified method is presented for determining the blade pitch motions resulting from prescribed swashplate oscillations or vice-versa.

Notation

A_n	cosine component of blade pitch motion
B_n	sine component of blade pitch motion
C	Harmonic swashplate oscillation amplitudes
N	number of blades
θ_i	pitch of blade number i
ϕ	$\frac{m}{N}(i-1)\,2\pi$
ψ	azimuth of rotor (blade no. 1)
ψ_i	azimuth of blade number i

Subscripts

C	cosine component
COL	collective oscillation
i	blade number i

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Subscripts (continued)

LAT	lateral oscillation
LONG	longitudinal oscillation
m	at frequency m-per-rev
n	harmonic number
S	sine component

Introduction

Reduction of rotor vibration by use of multicyclic control has long been advocated[1-4], and various schemes have been tested or are under investigation[5-10]. Some systems involve cams or actuators which rotate with the hub. Others have been restricted to specific harmonics, such as 2-per-rev or 4-per-rev, introduced by oscillating the swashplate via the non-rotating controls.

Most modern helicopters have boosted controls, usually including a high rate capability for stability augmentation systems. Thus, oscillation of the swashplate is often an inviting method of introducing multicyclic control. This note addresses determining which control harmonics are available by swashplate oscillation such that all blades have the same azimuthal pitch schedule. Specifically, what swashplate motions can produce the following pitch schedule for all N blades?

$$\theta_i = A_o - A_1 \cos \psi_i - B_1 \sin \psi_i - \ldots$$
$$\ldots - A_n \cos n \psi_i - B_n \sin n \psi_i$$

Analysis

For swashplate controlled rotors, the pitch of each blade is given by:

$$\theta_i = C_{COL} + C_{LAT} \cos \psi_i + C_{LONG} \sin \psi_i \tag{1}$$

(Note that swashplate gearing and control advance angle, which are functions of specific designs, are not included here). Now, let the swashplate oscillate at an integer harmonic of the rotor rotation frequency in each of the axes indicated above, and let the motion be composed of both cosine and sine components. Thus, for the collective oscillations at m-per-rev,

$$C_{COL} = C_{COL,\ O} + C_{COL,\ C} \cos m \psi + C_{COL,\ S} \sin m \psi$$

Noting that: $\psi_i = \psi - (i - 1) \frac{2\pi}{N}$, hence $m \psi = m \psi_i + \frac{m}{N} (i-1) 2\pi$, then

$$C_{COL} = C_{COL, O} + C_{COL, C} \cos [m \psi_i + \phi] + C_{COL, S} \sin [m \psi_i + \phi] \tag{2}$$

where: $\phi = \frac{m}{N} (i - 1) 2\pi$

For lateral cyclic oscillation:

$$C_{LAT} = C_{LAT, O} + C_{LAT, C} \cos m \psi + C_{LAT, S} \sin m \psi.$$

Then the term required for equation 1 is:

$$\begin{aligned} C_{LAT} \cos \psi_i = {} & C_{LAT, O} \cos \psi_i \\ & + \tfrac{1}{2} C_{LAT, C} \{\cos [(m-1) \psi_i + \phi] + \cos [(m+1) \psi_i + \phi]\} \\ & + \tfrac{1}{2} C_{LAT, S} \{\sin [(m-1) \psi_i + \phi] + \sin [(m+1) \psi_i + \phi]\} \end{aligned} \tag{3}$$

For longitudinal oscillations:

$$C_{LONG} = C_{LONG, O} + C_{LONG, C} \cos m \psi + C_{LONG, S} \sin m \psi,$$

and the corresponding term for equation 1 is:

$$\begin{aligned} C_{LONG} \sin \psi_i = {} & C_{LONG, O} \sin \psi_i \\ & + \tfrac{1}{2} C_{LONG, C} \{- \sin [(m-1) \psi_i + \phi] + \sin [(m+1) \psi_i + \phi]\} \\ & + \tfrac{1}{2} C_{LONG, S} \{\cos [(m-1) \psi_i + \phi] - \cos [(m+1) \psi_i + \phi]\} \end{aligned} \tag{4}$$

The pitch of blade i is then given by the sum of equations 2, 3 and 4. In order for the rotor to remain in track, θ_i must be the same for all i. This condition is satisfied if m = N, 2N, 3N, etc., so that:

$$\phi = \frac{m}{N} (i-1) 2\pi = 0, 2\pi, 4\pi, \text{ etc.}$$

Now, the blade pitch may be written either:

$$\theta_i = \theta_o + \sum_{n=1}^{K} (\theta_{nc} \cos n \psi_i + \theta_{ns} \sin n \psi_i)$$

or

$$\theta_i = A_o - \sum_{n=1}^{K} (A_n \cos n\,\psi_i + B_n \sin n\,\psi_i)$$

In either case, the first three terms define the steady swashplate positions. That is, (for m = N, 2N, etc.)

$$\theta_o = A_o = C_{COL,\,0}$$

$$\theta_{1c} = -A_1 = C_{LAT,\,0}$$

$$\theta_{1s} = -B_1 = C_{LONG,\,0}$$

The second and higher harmonics of blade pitch may then be found from:

$$\begin{bmatrix} \theta_{(m-1)c} \\ \theta_{(m-1)s} \\ \theta_{mc} \\ \theta_{ms} \\ \theta_{(m+1)c} \\ \theta_{(m+1)s} \end{bmatrix} = \begin{bmatrix} -A_{(m-1)} \\ -B_{(m-1)} \\ -A_m \\ -B_m \\ -A_{(m+1)} \\ -B_{(m+1)} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 \\ -\frac{1}{2} & 0 & 0 & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -\frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 \\ \frac{1}{2} & 0 & 0 & 0 & 0 & \frac{1}{2} \end{bmatrix} \begin{bmatrix} C_{LONG,\,C} \\ C_{LONG,\,S} \\ C_{COL,\,C} \\ C_{COL,\,S} \\ C_{LAT,\,C} \\ C_{LAT,\,S} \end{bmatrix} \tag{5}$$

and the inverse relation is:

$$\begin{bmatrix} C_{LONG,\,C} \\ C_{LONG,\,S} \\ C_{COL,\,C} \\ C_{COL,\,S} \\ C_{LAT,\,C} \\ C_{LAT,\,S} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \theta_{(m-1)c} \\ \theta_{(m-1)s} \\ \theta_{mc} \\ \theta_{ms} \\ \theta_{(m+1)c} \\ \theta_{(m+1)s} \end{bmatrix} \tag{6}$$

These same relationships may also be applied to control systems u-utilizing servo-flaps (such as the Controllable Twist Rotor) or pneumatic systems (such as jet flaps o circulation control), provided, of course, that these devices use swashplate type controls.

It is seen that for swashplate oscillations at m-per-rev (m = N, 2N, etc.), pitch oscillations may be obtained at harmonics of m-1, m, and m+1. To control the phase and amplitude of all three harmonics,

it is necessary to have individual control of amplitude and phase of collective, lateral, and longitudinal oscillations of the swashplate. The only restriction is that of m = N, 2N, etc., to maintain the rotor in track.

Two Bladed Rotors

$N = m = 2$.

For two blades and 2-per-rev oscillations of the swashplate, blade pitch harmonics of 1, 2 and 3 result. The amplitudes may be adjusted so as not to conflict with the steady swashplate position which is the normal control. The 2- and 3-per-rev pitch motions are then available for vibration control.

$N = 2,\ m = 2,\ 4$.

For m = 4, pitch harmonics of 3, 4, and 5 are available for vibration alleviation. Combining m = 2 and m = 4, the following equation may be used to obtain pitch motion harmonics of 2, 3, 4, and 5.

$$\begin{bmatrix} C_{LONG,\ C} \\ C_{LONG,\ S} \\ C_{COL,\ C} \\ C_{COL,\ S} \\ C_{LAT,\ C} \\ C_{LAT,\ S} \end{bmatrix}_{2(4)} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \theta_{2(4)C} \\ \theta_{2(4)S} \\ \theta_{3(5)C} \\ \theta_{3(5)S} \end{bmatrix}$$

Three-Bladed Rotors

For a rotor having three blades, all harmonics of blade pitch oscillations are possible. For example, m = 3 gives 2nd, 3rd, and 4th harmonics; m = 6 gives 5th, 6th and 7th, etc. This substantiates what one feels intuitively. Whatever pitch schedule is desired, the lower ends of the three pitch links determine a plane (the swashplate). Therefore, one concludes that by a proper swashplate motion schedule virtually any pitch schedule may be obtained. This includes those schedules which would produce out-of-track conditions for the rotor. To preclude out-of-track cases, the swashplate motions must correspond to those of equations 5 and 6, constrained to m = 3, 6, 9, etc. Shaw[3] discusses a case where N = m = 3.

Four-Bladed Rotors

For four-bladed rotors, m = 4 produces pitch harmonics of 3, 4, and 5; and m = 8 produces harmonics of 7, 8, and 9. Although one could de-

vise a system (such as using two swashplates) to obtain the missing 2nd, 6th, etc. harmonics, it is possible that interharmonic coupling[5] via the system dynamics would produce some quantity of these harmonics, and compensate for this lack.

Five- or more-Bladed Rotors

In these cases, we must have $m \geq 5$, and the harmonics of pitch motion are more restricted (more harmonics are missing). Equations 5 and 6 still apply. For five-bladed rotors, only the 4th, 5th, and 6th harmonics are available ($m = 5$). These restrictions may not be severe however, since it has been shown[11] that the main harmonics of vibration transmitted to the fuselage are N-1, N and N+1, in the rotating reference frame, and N in the nonrotating frame. It may indeed be restrictive if the control inputs are desired to reduce the harmonic loading applied to the blades, or to improve rotor performance[12].

Swashplate Oscillation at Other Frequencies

It is possible to oscillate the swashplate at other frequencies than those discussed herein ($m \neq N, 2N, \ldots$). Such oscillations would lead to mismatched pitch variations, out-of-track rotor operation, and possibly higher vibration. However, it may be possible that certain controlled higher harmonic out-of-track conditions could improve vibration, blade loads, and performance. Equations 5 and 6 would still apply to the master blade and for the amplitudes of pitch motion for the other blades. Phasing of the other blade harmonics may be found by applying equations 2, 3, and 4.

Conclusions

It has been shown herein that for two-, three-, or four-bladed rotors, simple oscillation of the nonrotating swashplate controls can produce prescribed blade pitch schedules of the sort which have been suggested for vibration alleviation. Equations were given which relate the swashplate motions to the resulting blade pitch schedules.

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16. Abstract

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